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Flow Through Axially Aligned Sequential Apertures of the Orifice and Borda Types

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FLOW THROUGH AXIALLY ALIGNED SEQUENTIAL APERTURES OF THE ORIFICE AND BORDA TYPES

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NOMENCLATURE

C_f	flow coefficient
D	diameter
G	mass flow rate
G*	flow normalizing parameter, $\sqrt{P_c \rho_c / Z_c}$, 6010 g/cm^2 - s for nitrogen
H	enthalpy
ℓ	length of orifice or Borda
L	length of spacer
P	pressure
S	entropy
T	temperature
u	velocity
V	specific volume
Z	compressibility
$\rho = 1/V$	density

*Current address: Miami University, Oxford, Ohio.

SUBSCRIPTS:

c	thermodynamic critical
e	exit
h	equivalent diameter
i	ith sequential inlet
o	stagnation or reference
r	reduced by normalizing parameter

INTRODUCTION

Sharp edge as well as contoured inlet configuration are common to fluid machinery components, such as labyrinth seals, and heat transfer devices. In many cases, the details of the flow dynamics in these systems are not well understood. Such was the case when an unusual separation phenomenon was encountered in the study of a three stepped sequential seal used in the shuttle engine (1). With the seal in the fully eccentric position, the flow appeared to separate and jet throughout the third stage length in the maximum clearance of the annular channel.

These unusual results provoked a series of choked fluid flow tests in the tubes with single sharp edge orifice and Borda type inlets (2-5), which demonstrated that the jetting phenomenon could occur over a rather wide range of fluid state conditions. The jetting occurred principally at low inlet temperatures and inlet pressure higher than saturation, and appeared nearly independent of the inlet geometry cross section.

The next phase was to look into sequential inlets. The authors found only a few studies in the open literature on the flow phenomenon in axially aligned sequential inlets.

One such study was that of Boscole, Martin, and Donnis (6), who were primarily interested in the improvement of flowmeters. Recently, Benchert and

Wachter (7), presented a thorough study of the stability of see-through and leaved labyrinth type seals. Iwatsubo (8) also studied the stability of flows in labyrinth seal cavities. His results seem to be nearly the analytical complement to the experimental work of Benchert and Wachter (14). Komotori and Mori (9) studied the isentropic expansion of a perfect gas through labyrinth seals. While not directly applicable, these studies serve as limiting cases and guides to experimental and analysis.

Consequently, this paper will provide a comparison of flow rate and pressure profile characteristics for four sequential axially aligned aperatures of the Borda and orifice type at nominal separation distances of 0.7 and 30 diameters over a wide range of fluid state conditions including liquid, gas and those in between.

FLOW VISUALIZATION

A flow visualization study was carried out on the water table to determine some characteristics of flows in sequential inlets. Lucite models were made of orifice and Borda inlets, using ℓ/D dimensions similar to those the authors expected to apply to the test apparatus. The models were then run on the water table, where the inlet water level was maintained at nearly two channel widths and a red dye used to mark the flow paths.

"Jetting" is prevalent when the four models are placed to form a continuous channel, figures 1.a.1 and 1.b.1, for the Borda and orifice, respectively. At a spacing of one third of the inlet diameter, figures 1.a.2 and 1.b.2, "jetting" is still somewhat prevalent. The flow through the orifice tends to filter into the cavities, whereas the flow through the Borda does not. The Borda tends to align the flow and produces more carryover. At a spacing of 2 to 3 diameters, shown in figures 1.a.3 and 1.b.3, oscillations are observed which are a maximum at this spacing. The orifice oscillations are a little more violent than those of the Borda. Both the flows in the Borda and orifice cases, figures 1.a.4 and 1.b.4, are nearly independent of the reservoir at a spacing of 16 diameters.

While the effects of compressibility were not simulated, analogies to potential flow were noted and used. A more complete selection of observations and photographs are given in references 10 and 11.

APPARATUS AND INSTRUMENTATION

From the flow visualization studies, it became apparent that stable flow could be anticipated for sequential inlet spacings less than one diameter and for spacings of more than 20 diameters. The inlets were designed to be similar to those of references 2 and 3, with small spacers of 0.32 cm (0.125 in.) for the orifice and 1.03 cm (0.407 in.) for the Borda and 15.24 cm (6 in.) large spacers for both. This provided two fixed spacings between the inlets of nominally 0.7 (0.8, Borda and 0.66, orifice) and 30 diameters (30, Borda and 32, orifice), respectively. Note that the orifice is not a "sharp edge orifice" but has $\ell/D = 0.5$; the Borda $\ell/D = 1.9$.

The flow facility, a blow down type, was basically that described in reference 12, but modified to accommodate the sequential inlet configurations (10-11). The working fluid was nitrogen.

A schematic of the four sequential Borda inlet configuration with 1.03 cm (0.47 in.) spacers is illustrated in figure 2(a), which also provides details of the Borda inlet geometry and pressure tap locations. The four sequential orifice inlet configuration with 0.32 cm (0.125 in.) spacers is shown as figure 2(b). Detailed photographs of the Borda and orifice inlets are given as figures 3(a) and (b), respectively.

A schematic of the four sequential inlet configuration with 15.24 cm (6 in.) spacers is shown as figure 2(c), which also gives the pressure tap locations on the 15.24 cm (6 in.) spacers. The schematic applies for both the orifice and Borda geometries.

The configuration was "sandwiched" between inlet and outlet flange adaptors to accommodate the multiple lengths with the multiple surfaces being statisfactorily sealed by thin mylar gaskets between flat faces.

The pressure data were recorded as described in references 10 to 12. Again, the working fluid is nitrogen.

ANALYSIS

In an attempt to treat the sequential inlet problem analytically, we assume the entire process to be adiabatic with a series of isentropic expansions across each inlet followed by an isobaric recovery in a "mixing chamber" to the adiabatic locus as illustrated in figure 4. A flow coefficient is introduced in an attempt to account for the pressure drop recovery following each inlet and other effects such as carryover. Such a procedure was used to predict flow rate and pressure ratios of the four Borda and orifice inlet configurations with some success (10-11). The procedure is also quite similar to the approach given by Komotori and Mori (9), for flow through labyrinth seals.

At the present time we will consider only the simplest cases marked gas and liquid on figure 4.

The governing equations, described in reference 10, may be written:

$$\left(\frac{G}{C_f}\right)^2 = 2\rho_i^2\,(H_o - H_i)$$

Constraints:

Isentropic

$$S(P_o,T_o)_i = S(P_e,T_e)_i$$

Isobaric

$$P_{e_i} = P_{o_{i+1}}$$

Critical flow (choked)

$$G_m^2\left(\frac{dV}{dP}\right)_e\bigg|_{i=4} = -1$$

where

$$G_m^2 = \frac{1}{V^2}\int_P^{P_o} V\,dP$$

While the governing equations appear straight forward, their solution is not; the computational procedure initiated in reference 10 is still being developed. A constant flow coefficient of 0.75 was assumed to account for entrance losses with low carryover thus expediting the development of a solution.

At the 30 diameter spacing, we assume each inlet to act independent of the previous inlet. In general, the gas data are easier to handle than the liquid, but in either case, one must assumed (1) the pressure ratio across the first inlet, (2) that the choking condition applies to the last inlet, and (3) that the iteration will converge to a solution.

For the limiting case of a perfect gas, the results are in good agreement with Komotori and Mori (9).

At the 0.7 diameter spacing the four sequential inlet configuration is assumed to behave as a single inlet.

RESULTS

Data were taken over a wide range of temperatures $0.68 < Tr <$ gas (86 to 300 K) and pressures to $Pr = 2$ (to 7 MPa), and are presented in two sections: (1) flow rate and (2) pressure profiles.

FLOW RATE

Reduced flow rate as a function of reduced pressure at selected isotherms are presented in figures 5(a) to (d). The reduced flow rate is determined by:

$$Gr = G/G^*$$

where G^* can be determined by the extended corresponding states theory (10,13,14). Although no verification of the extension of the results herein to other fluids is presented (13-16) suggest that the principle can be applied.

The flow rates between the four Borda and four orifice configuration at nominally 30 diameters show nearly the same trends, figures 5(b) and (d). The calculated curves for the liquid and gas approximate the experimental curves fairly well. The fluid properties were obtained using the computer code GASP (17).

At nominally 0.7 diameters, figures 5(a) and (c), the flow rates again are very similar. These flow rates, as compared to those of the 30 diameter spacings are substantially higher, and closely correspond to flows through single inlets (2,3).

In references 2, 3, 10, and 11 the flow rates were ratioed to those predicted for two phase choked flow through a venturi. This ratio is defined as a flow coefficient. Even though in these experiments, four such inlets are aligned axially and it belies further understanding of the flow details, we will apply the same technique.

The flow coefficient (C_f) for the four inlet configuration becomes:

$$C_f = Gr/Gr\text{-venturi}$$

where Gr-venturi is calculated using the homogeneous non-equilibrium model (single inlet).

At the 30 diameter nominal spacing, $C_f = 0.35$ for the orifice and 0.36 for the Borda at the 0.68 reduced inlet stagnation temperature isotherm, while for the gas the value of C_f increases to 0.51 for the orifice and 0.52 for the Borda, as illustrated in figures 6(a) and (b).

The trend of increasing flow coefficient with increasing temperature is not unusual. It was found for tubes with single Borda and orifice type inlets to 105 ℓ/D (2-4). Using the C_f locus for a 53 ℓ/D tube with a single Borda inlet (2), and a 53 ℓ/D tube with a single orifice inlet (3), as background reference curves, the C_f variation for the four orifice and Borda inlets is given on figures 6(a) and (b). The deviation bars represent uncertainties (with pressure for example), at selected isotherms. The non-equilibrium model (16), allows a certain degree of metastability which becomes increasingly important for inlet stagnation pressure approaching saturation.

As was pointed out earlier, the flow coefficient technique does little to promote understanding of the complex four sequential inlet flow phenomena, but it is expedient and characterizes the black box nature of the system.

As was the case with the nominal 30 diameter spacing, the flow coefficient for the nominal 0.7 diameter spacing varies. Using the single 53 ℓ/D Borda inlet and the 53 ℓ/D orifice inlet as background curves and the homogeneous non-equilibrium model in the calculated value of Gr, the variations of C_f with reduced inlet stagnation temperature are given in figures 6(a) and (b) for the 0.7 diameter case. Again, the four orifice and four Borda inlets show similar trends at 0.7 diameters spacings as reflected in mass flux rates, figures 5(a) and (c).

While the level of C_f changes from the "sharp-edge" value of 0.6 to 0.8 in the gas, the trends appear to be similar to those of the 30 diameter spacing and that of a tube with a single Borda of orifice type inlet (2,3). Recall that $\ell/D = 1.9$, Borda and $\ell/D = 0.5$, orifice.

PRESSURE PROFILES

A dramatic change in pressure profiles occurs for both the gas and liquid cases as the spacings change from 0.7 to 30 diameters.

At the 30 diameter spacing, the pressure profiles exhibit a sharp drop at the inlet, recover somewhat within the Borda or orifice inlets, figures 7(a) and (b), respectively, and show a sharp drop at the fourth inlet. At lower inlet stagnation temperatures, the profile is flat, indicating jetting (1,2,3,10,11). Pressure recovery varies somewhat with each inlet as temperature changes, but is altered most in the fourth inlet.

At the 0.7 diameter spacing, the pressure profiles resemble those of a free jet, at the lower inlet stagnation temperatures and those with significant carryover at higher temperatures, figures 7(c) and (d) for the Borda and orifice, respectively. Such profiles are analogous to those noted for single Borda and orifice type inlets and in the shuttle seal study (1-3). Under these conditions, the fluid can flow virtually unimpeded through the four sequential Borda or orifice inlets, even though they are separated by a nominal spacer length of 0.7 diameters. Note that the orifice type inlet configuration is much more sensitive to changes in stagnation temperature than are the Borda inlets which appear to direct the flow.

The partial pressure recovery in the sequential Borda case is concave downward as illustrated in figures 7(a) and (c), whereas in the orifice case, figures 7(b) and (d), the partial pressure recovery is concave upward. This may indicate that the sequential Borda tends to recover more fully.

Further comparisons and other data can be found in references 1, 2, 3, 10, and 11 including the effects of backpressure. Generally, significant variations in backpressure must be applied to eliminate the jetting profiles.

These results demonstrate that jetting can occur even with disjoint sequential inlets and elevated backpressures and further defines the nature of the flow separations found in references 1 to 3.

SUMMARY

Choked flow rate and pressure profile data for four-axially aligned-sequential-Borda and orifice type inlet configurations separated by nominal spacings of 0.7 and 30 diameters, have been studied.

For either the Borda or orifice inlets at the 0.7 or 30 diameter spacing, a flow coefficient plot as a function of reduced temperature could be used to group the results. However, such practice adds little to the understanding of flow details and the deviations with pressure for example, are not yet explained. At the 30 diameter spacing, C_f is low indicating little carryover while at the 0.7 diameter spacing, C_f is higher indicating substantial carryover.

At a spacing of 30 diameters, the pressure profiles drop sharply at the inlet of each of the Borda or orifice type inlets and are followed by some recovery; the exception being the last inlet where fluid jetting can occur at the lower inlet stagnation temperatures.

At a spacing of 0.7 diameters, fluid jetting through all four Borda or orifice inlets was prevelant at low inlet stagnation temperatures, with choking controlled at the entrance of the first inlet and at the exit of the last to the point of being choked at either place. The application of significant backpressure does not alter fluid jetting.

These results agree with data for jetting in tubes with single Borda or sharp edge orifice type inlets. They are also in qualitative agreement with water table flow visualization studies used to delineate regions of fluid stability and instability.

Analytic modeling is quite complex, but a simplistic model of the 30 diameter spacing cases appears to give reasonable agreement with limited gas and liquid data for a fixed flow coefficient of 0.75 (low carryover). Further, agreement with the labyrinth seal analysis of Komotori and Mori (9), for the limiting case of a perfect gas indicates that axisymmetric results may be applied to axisymmetric annular passage flows.

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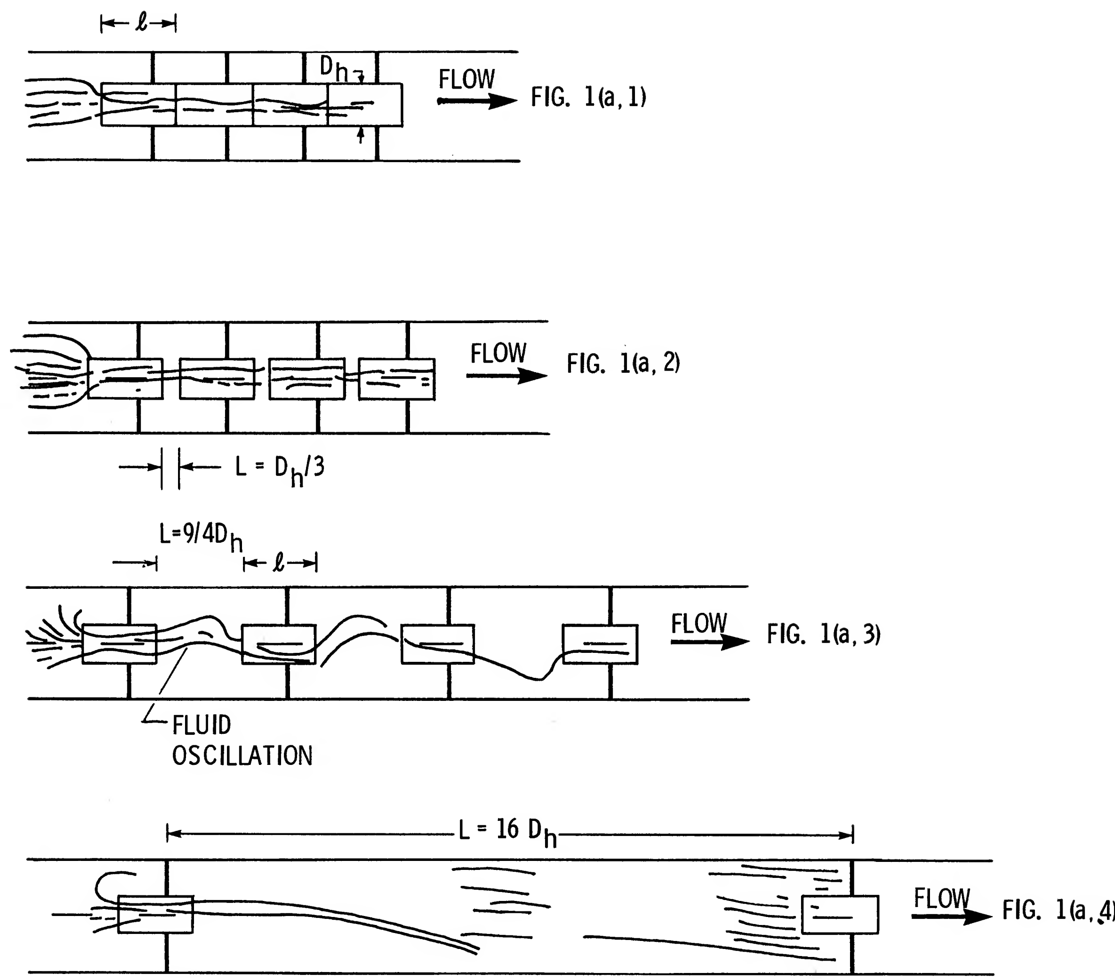
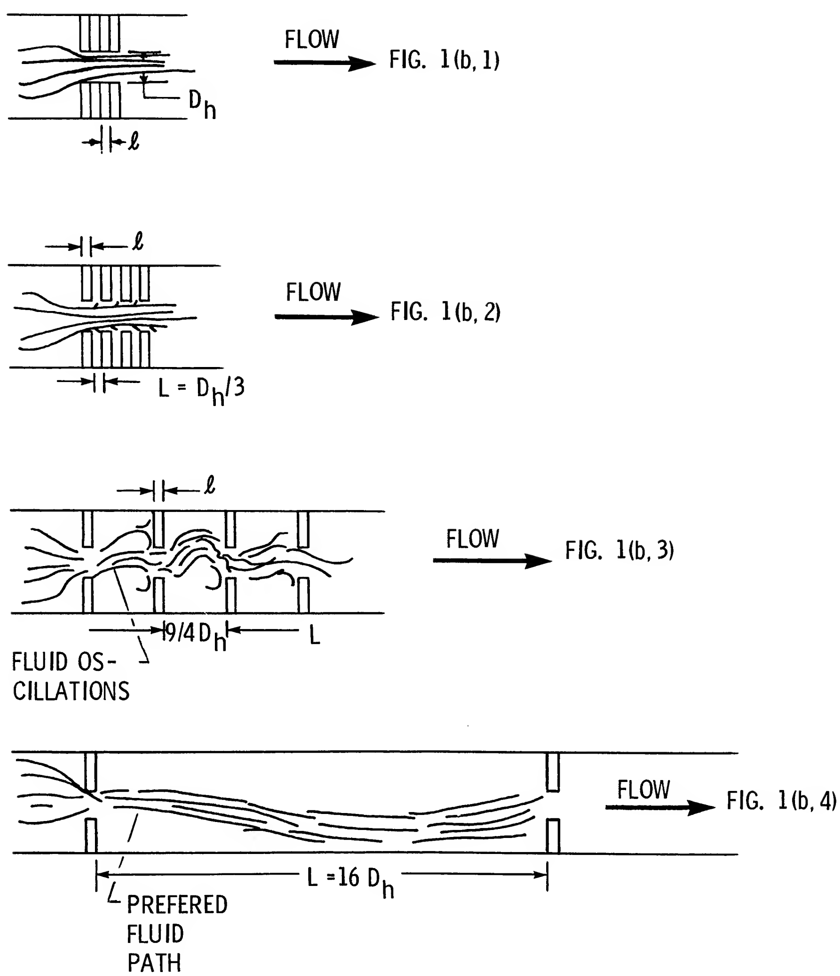


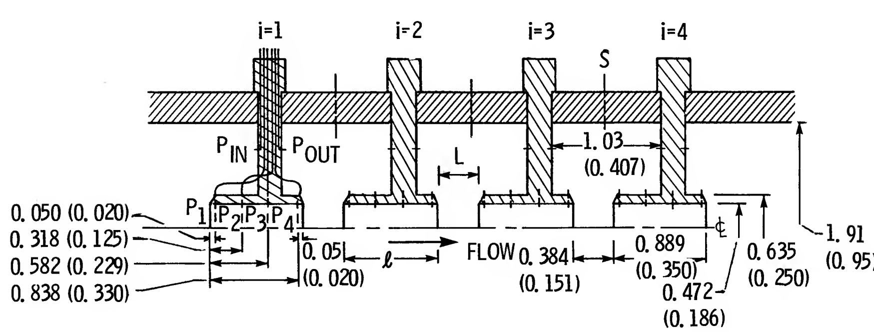
(a) FOUR BORDA.

Figure 1. - Schematic of water flow visualization in sequential inlets.



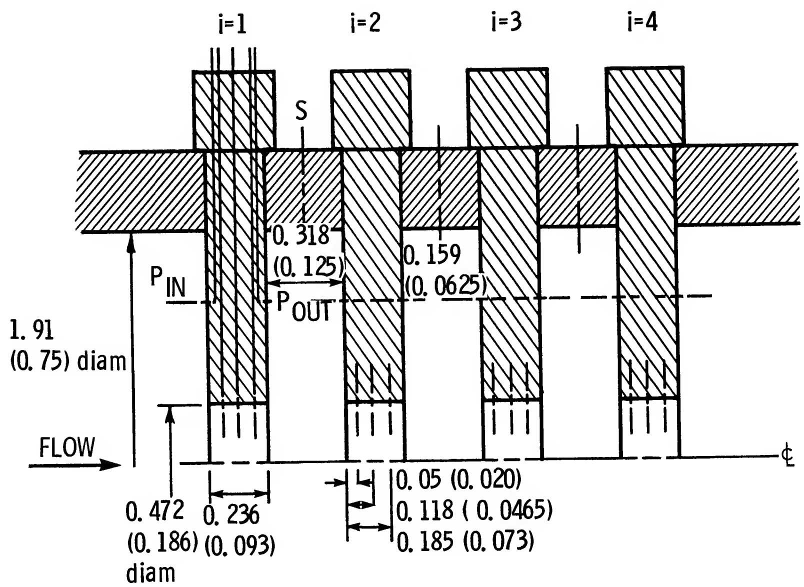
(b) FOUR ORIFICE.

Figure 1. - Continued



(a) FOUR BORDA WITH 1.03 cm (0.407") SPACER.

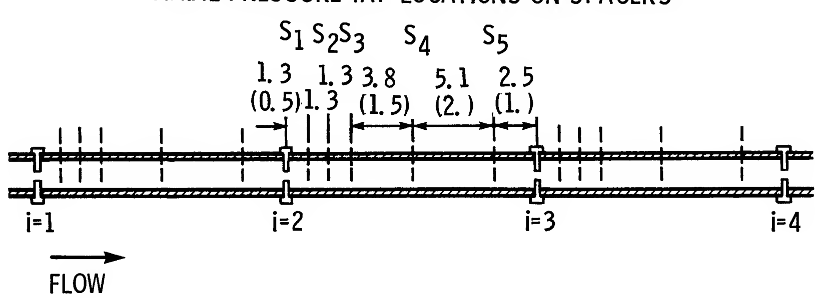
Figure 2. - Schematic of four sequential inlet test section with spacers.



(b) FOUR ORIFICE WITH 0.32 cm (0.125") SPACER.

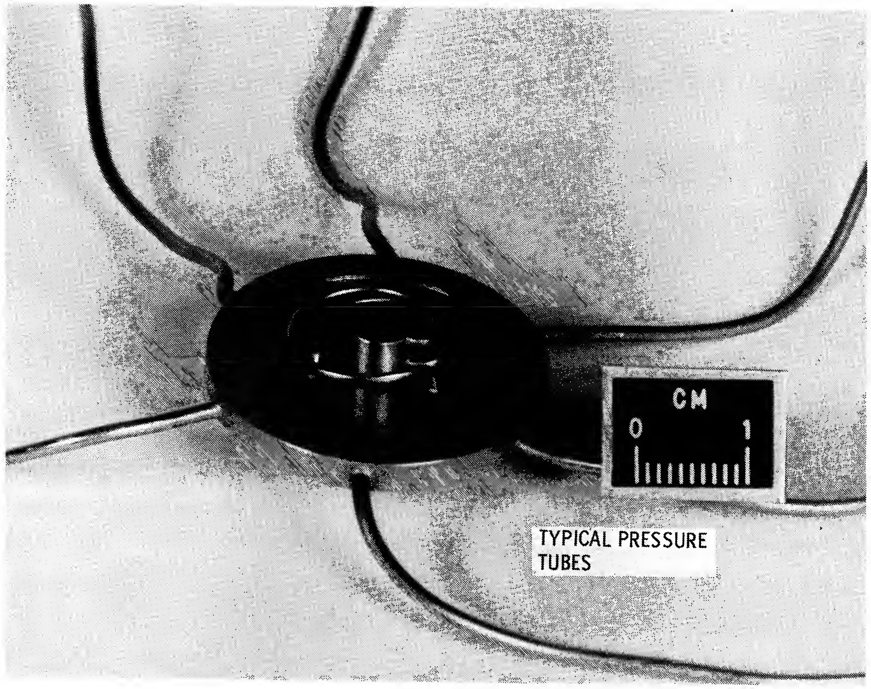
Figure 2. - Continued.

AXIAL PRESSURE TAP LOCATIONS ON SPACERS



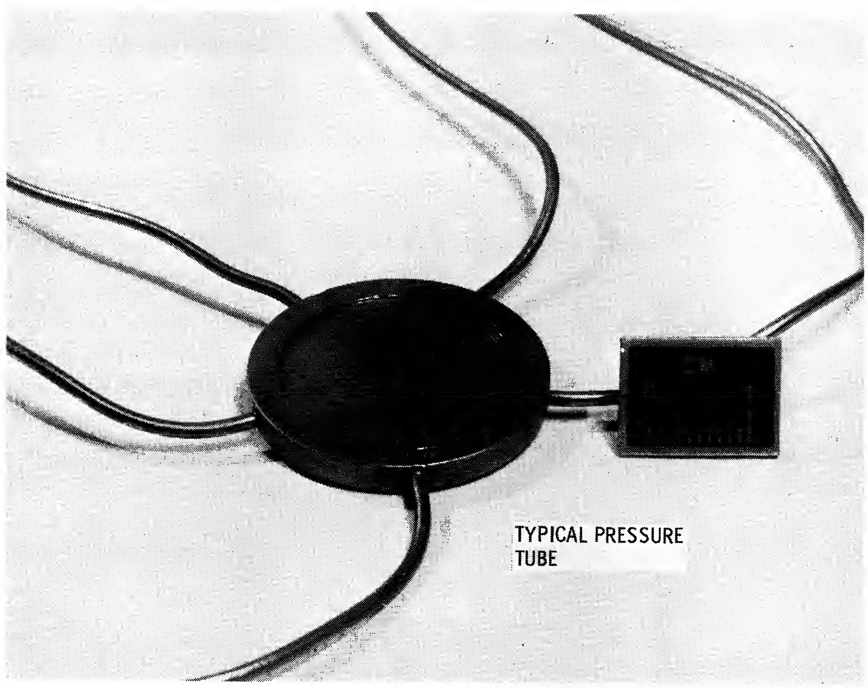
(c) FOUR ORIFICE WITH 15.24 cm (6") SPACER.

Figure 2. - Concluded.



(a) BORDA.

Figure 3. - Close-up photograph of inlet.



(b) ORIFICE.

Figure 3. - Concluded.

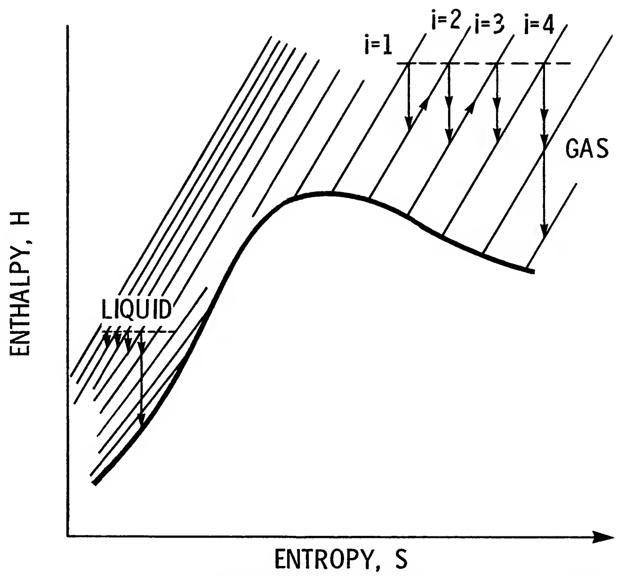
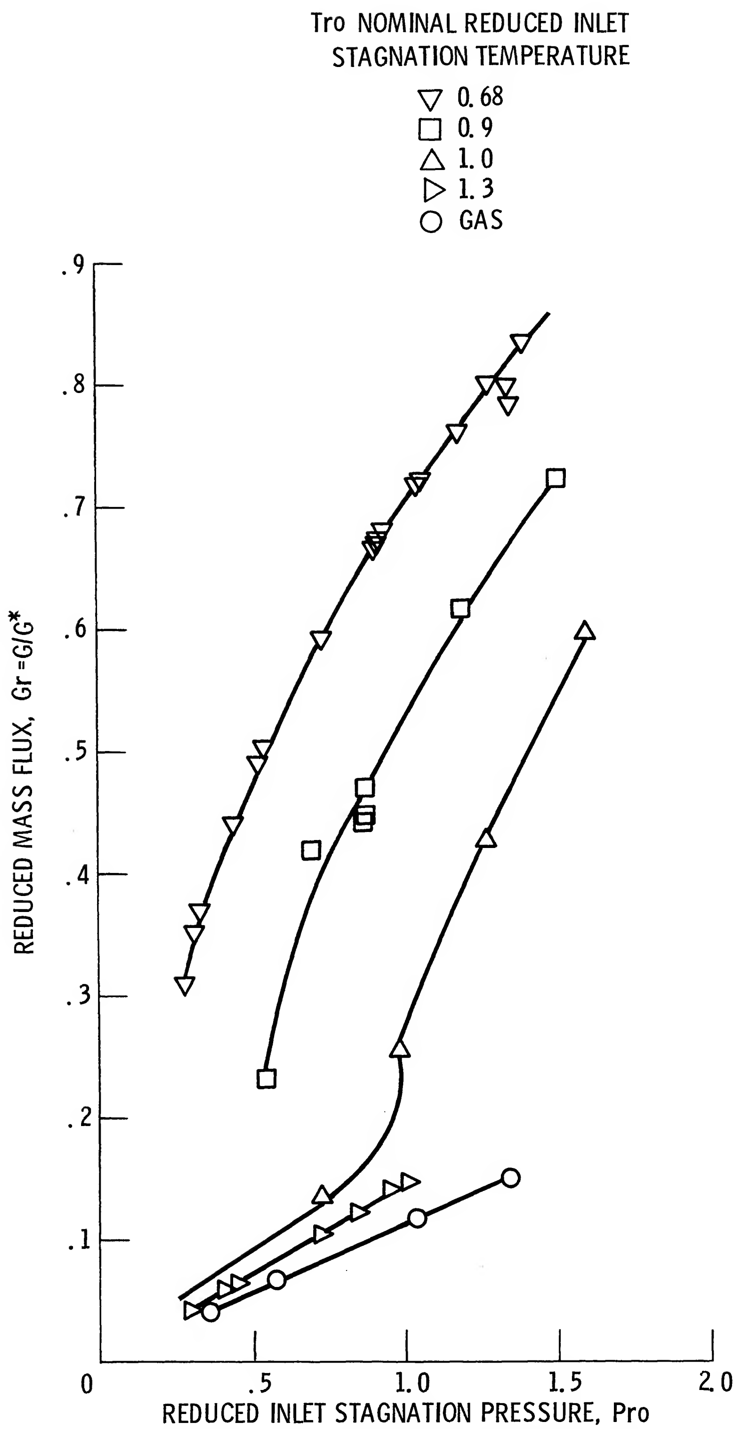
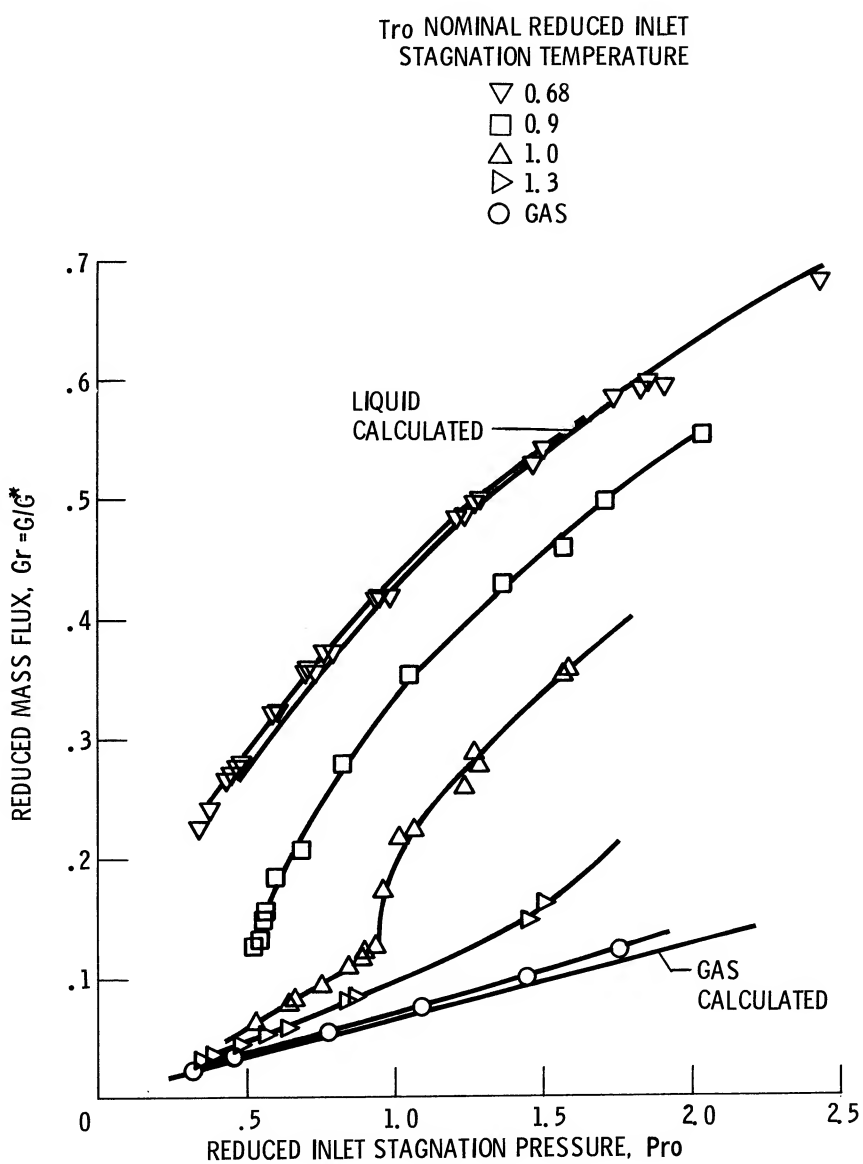


Figure 4. - Process path four sequential inlet configuration on entropy - enthalpy diagram.



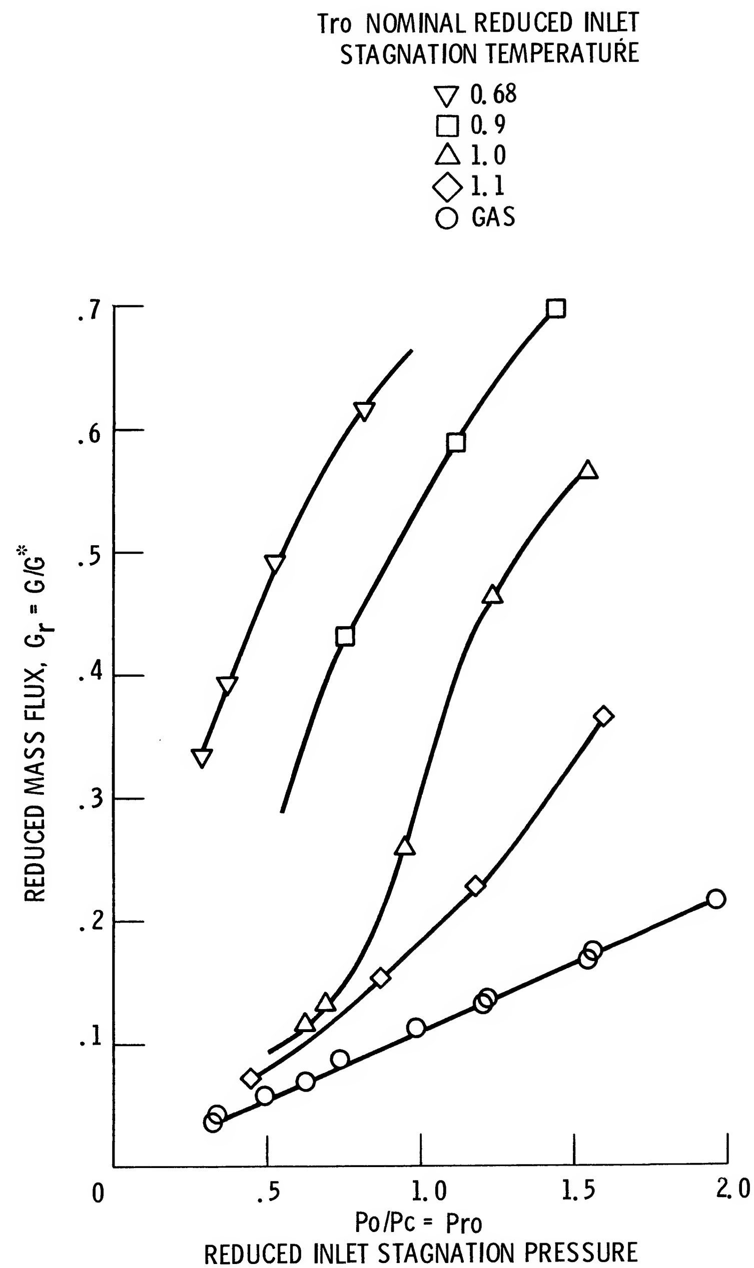
(a) FOUR BORDA AT 1.03 cm (0.407") SPACERS.

Figure 5. - Reduced mass flux as a function of reduced temperature.



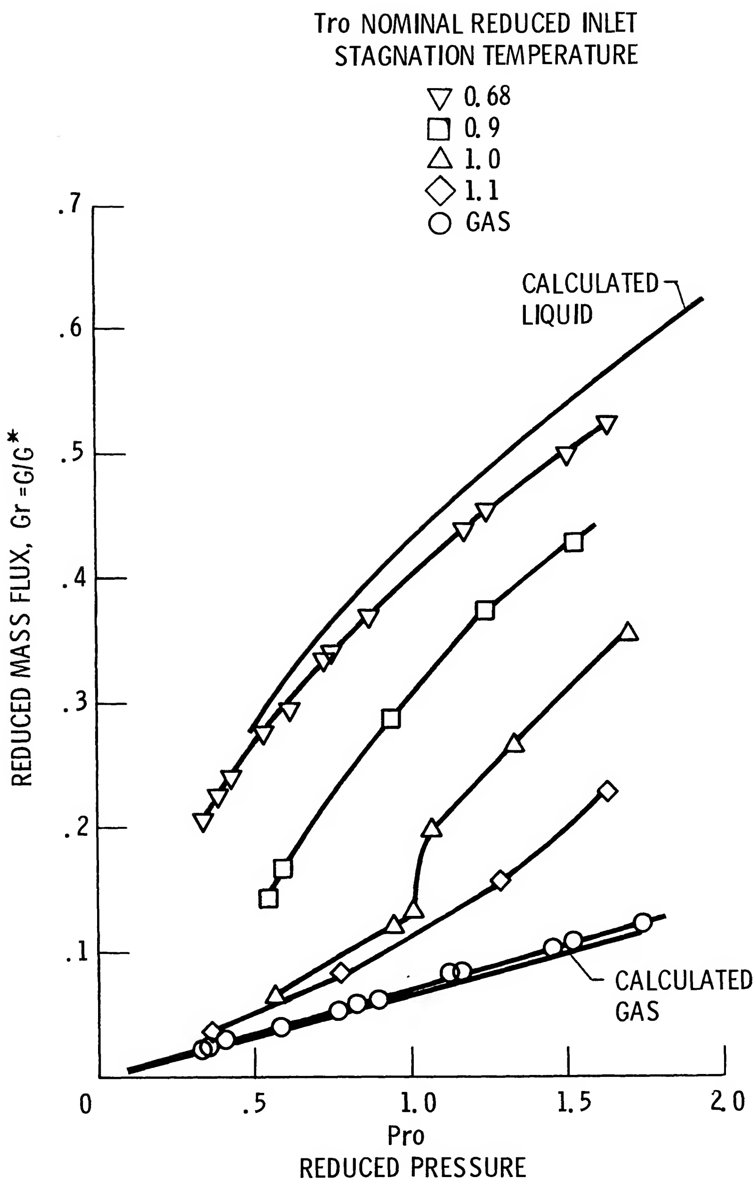
(b) FOUR BORDA AT 15.24 cm (6") SPACERS.

Figure 5. - Continued.



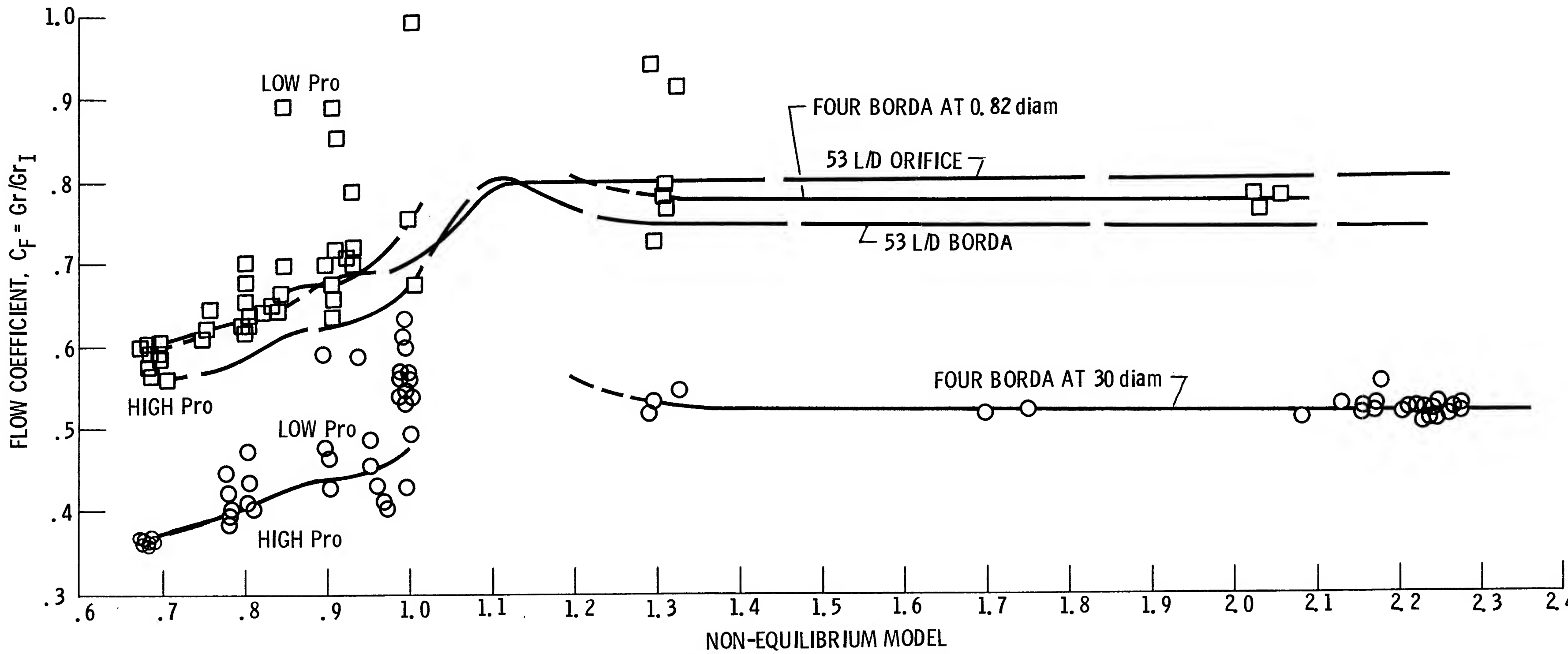
(c) FOUR ORIFICE AT 0.32 cm (0.125") SPACERS.

Figure 5. - Continued.



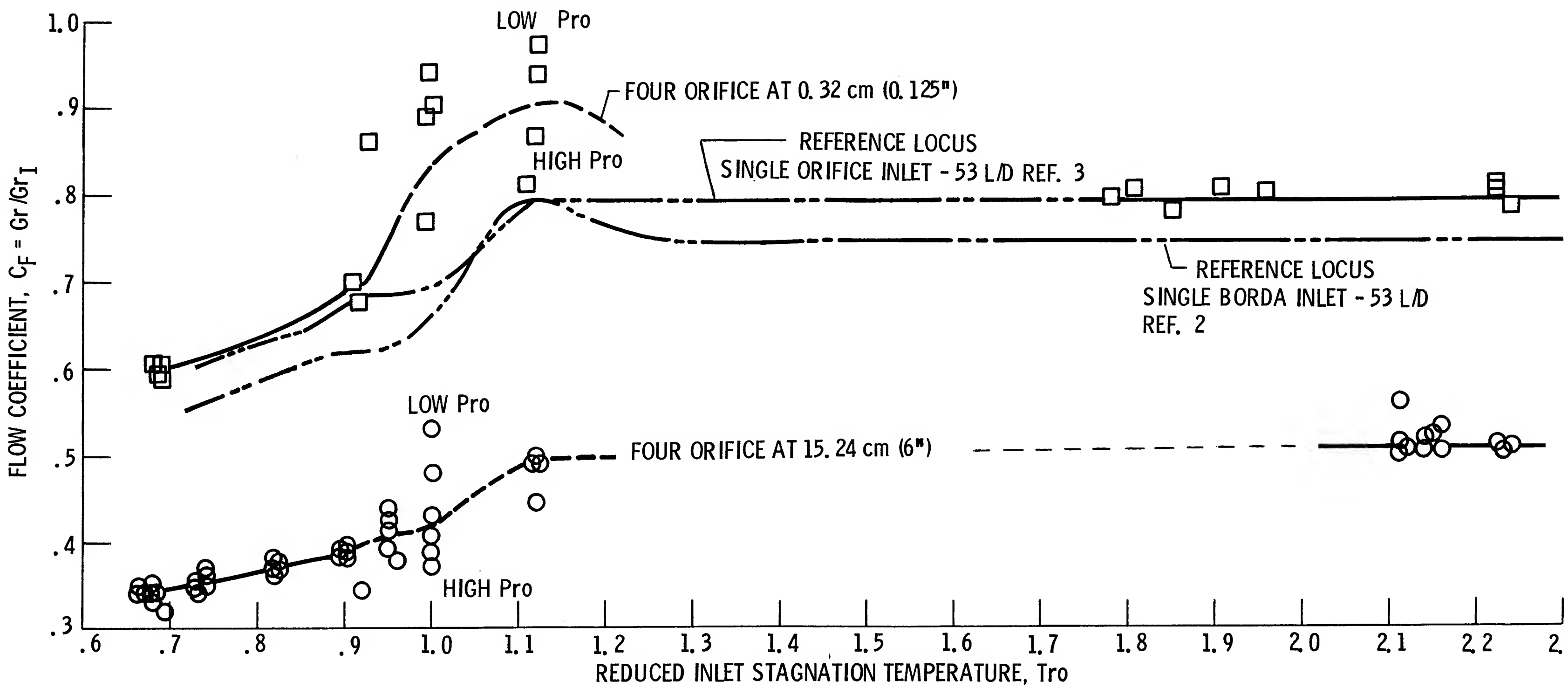
(d) FOUR ORIFICE AT 15.24 cm (6") SPACERS.

Figure 5. - Concluded.



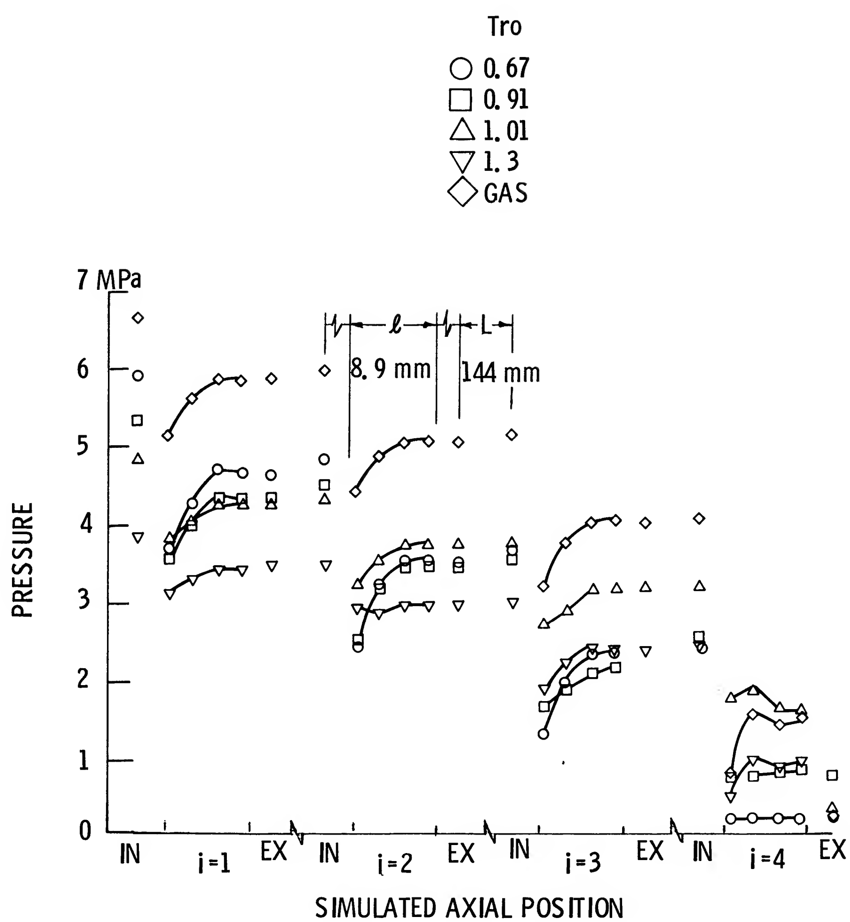
(a) FOUR SEQUENTIAL BORDA.

Figure 6. - Flow coefficient as a function of reduced temperature.

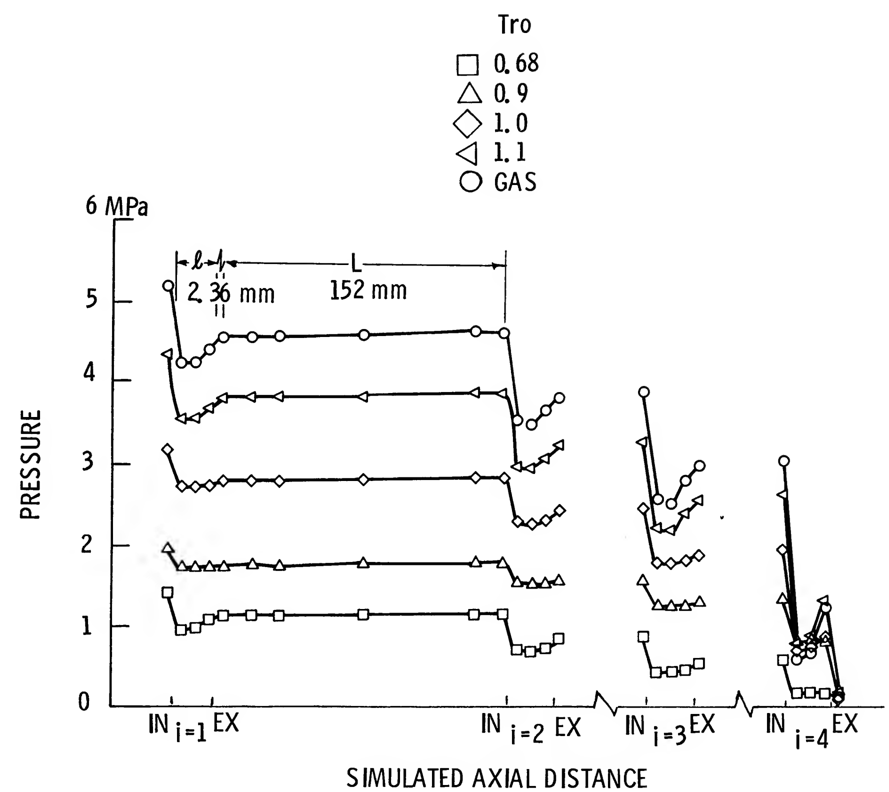


(b) FOUR SEQUENTIAL ORIFICE.

Figure 6. - Concluded



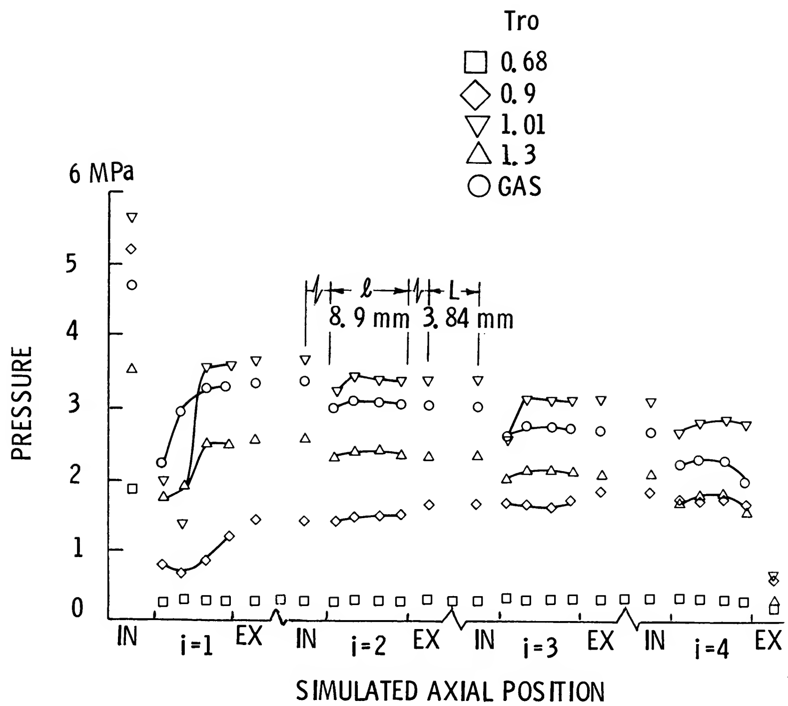
(a) FOUR BORDA AT 15.24 cm (6") SPACERS.



(b) FOUR ORIFICE AT 15.24 cm (6") SPACERS.

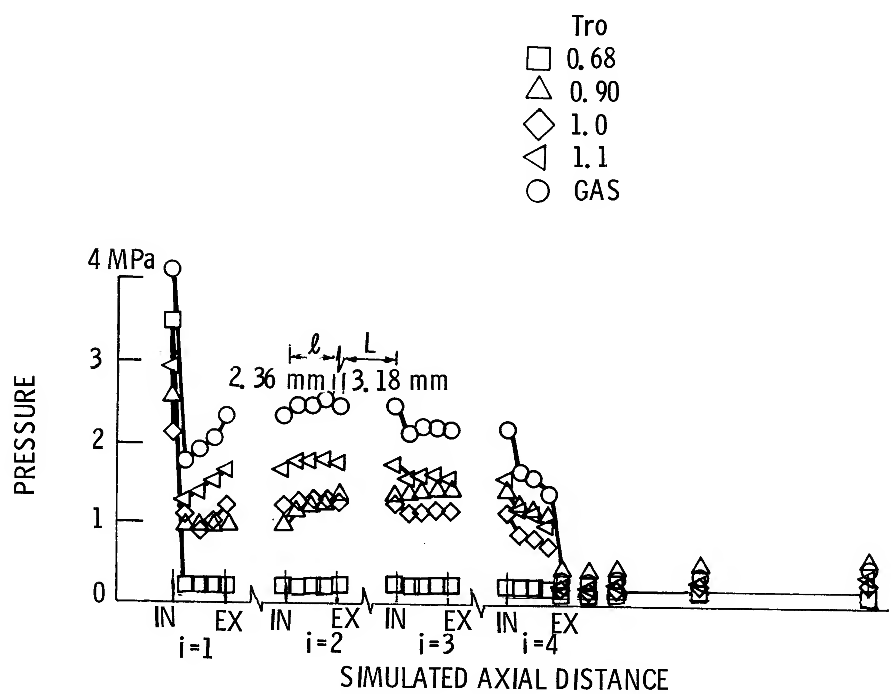
Figure 7. - Pressure profiles for sequential inlets.

Figure 7. - Continued.



(c) FOUR BORDA AT 1.03 cm (0.407") SPACERS.

Figure 7. - Continued.



(d) FOUR ORIFICE AT 0.32 cm (0.125") SPACERS.

Figure 7. - Concluded.

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16. Abstract

Choked flow rate and pressure profile data were taken and studied for two axially aligned sequential configurations consisting of: (1) Four Borda type inlets of 1.9 ℓ/D with two separation distances of 0.8 and 30 diameters. (2) Four orifice type inlets of 0.5 ℓ/D with two separation distances of 0.66 and 32 diameters. Data were taken using fluid nitrogen over the reduced inlet temperature and pressure range $0.68 < T/T_c <$ gas and P/P_c to 2. A flow-coefficient reduced-temperature plot can be used to represent the flow rate data for each geometry. At the larger separation distances, the pressure profiles dropped sharply at the entrance and partially recovered within each of the Borda and orifice inlet configurations; the exception being the last inlet where at low entrance temperatures, fluid jetting could occur. For the smaller spacings fluid jetting was prevalent throughout each of the inlet configurations at lower inlet temperatures. These results are in qualitative agreement with data of tubes with single Borda or sharp-edge orifice type inlets to 105 ℓ/D and water flow visualization studies.

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